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An Improved ICI Self Cancellation Method to Reduce ICI in OFDM Systems

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Abstract*: Orthogonal frequency division multiplexing systems are highly sensitive to frequency offset introduced by the wireless channels. This frequency offset destroys the orthogonality between the OFDM subcarriers and causes inter-carrier interference (ICI). Self-cancellation schemes which have been developed to combat the impact of frequency offset on OFDM systems have received a lot of attention due to their simple implementation and high efficiency. This paper proposes an efficient ICI self cancellation scheme to combat the impact of ICI on OFDM systems. In this scheme at the transmitter side, one data symbol is modulated onto four subcarriers with appropriate weighting coefficients. At the receiver side, the linear combination of the received signals on these subcarriers leads to a sufficient reduction in ICI. A detailed analysis and simulation over AWGN channel proves that the proposed scheme achieves better BER (Bit Error Rate) performance and CIR improvement than the existing self cancellation schemes.

Index Terms*: Orthogonal frequency division multiplexing (OFDM), inter-carrier interference (ICI), ICI self cancellation, frequency offset, carrier-to-interference ratio (CIR).

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) systems though quite effective in avoiding inter-symbol interference (ISI) due to multipath delay [1], suffers from the front-end distortions such as carrier frequency offset (CFO) which destroys the orthogonality among subcarriers in one OFDM symbol and thus causing inter-carrier interference (ICI) [1], [3]. These frequency differences are often caused by the Doppler shift and/or mismatch between oscillators in the transmitter and receiver [1]. This ICI due to frequency offset can be reduced by decreasing the sensitivity of the OFDM systems towards the frequency offset errors.

A number of techniques have been developed for reducing ICI in OFDM systems. These techniques include the frequency domain equalization [4], the time domain windowing [5], [9] and the ICI self-cancellation schemes [2], [6], [7] and [10]. Among these, much attention has been paid to the ICI self cancellation scheme because of its implementation simplicity. Its main idea is to map one data symbol onto a group of subcarriers with predefined weighting coefficients. By doing so, the ICI signals generated within a group could be "self-cancelled". Fig. 1 depicts a simplified block diagram of an OFDM system with ICI self-cancellation. In the figure d_k, $k = 0,1,..,\frac{N}{2} - 1$ and X_k, $k = 0,1,..,N-1$ denote the data symbols before and after ICI cancelling modulation, respectively. *N* is the total number of sub-carriers. Among the various ICI self cancellation methods, it has been shown that the Symmetric Conjugate Symbol Repetition (SCSR) method [10] (where the mapping is done as $X_k = d_k$, $X_{N-1-k} = -d^*_k$) has the best bit error rate (BER) performance for frequency offset suppression when compared to the BER performances of the adjacent ICI self-cancellation method (with $X_{2k} = d_k, X_{2k+1} = -d_k$) [2], symmetric ICI self cancellation method (with $X_k = d_k$, $X_{N-1-k} = -d_k$) [7] and adjacent conjugate symbol repetition (ACSR) (with $X_{2k} = d_k$, $X_{2k+1} = -d^*_k$) [10].

In this paper, we propose a new ICI self cancellation scheme where one data symbol is mapped onto four subcarriers. This mapping on subcarriers further enhances the performance of the OFDM system in terms of reduced BER and improved average carrier-to-interference power ratio (CIR). The CIR specifies the ICI level existing in the received signals [8]. In this paper we present a theoretical expression for CIR for the proposed self cancellation scheme. Further, we have also presented analytical and simulation results to show the performance improvement of the proposed self cancellation scheme over that of SCSR and adjacent ICI self cancellation scheme. In the subsequent, we will refer adjacent ICI self-cancellation scheme, as "Adjacent Symbol Repetition (ASR)".

II. SYSTEM MODEL

In an OFDM system, the complex baseband OFDM signal after the IFFT block at the transmitter can be expressed as

$$x(n)=\frac{1}{N}\sum_{k=0}^{N-1} X(k)e^{j\frac{2\pi nk}{N}}, \qquad n=0,1,2...N-1 \qquad (1)$$

where *N* is the total number of subcarriers, *X*(*k*) denotes the transmitted quadrature amplitude modulation (QAM) or M-ary phase-shift keying (PSK) modulated symbol on the subcarrier *k* with *k* = 0, 1, 2, …, *N* −1.

The received signal after being affected by the frequency offset can be written as

$$y(n) = x(n)e^{j\frac{2\ n\varepsilon}{N}} + w(n) \qquad (2)$$

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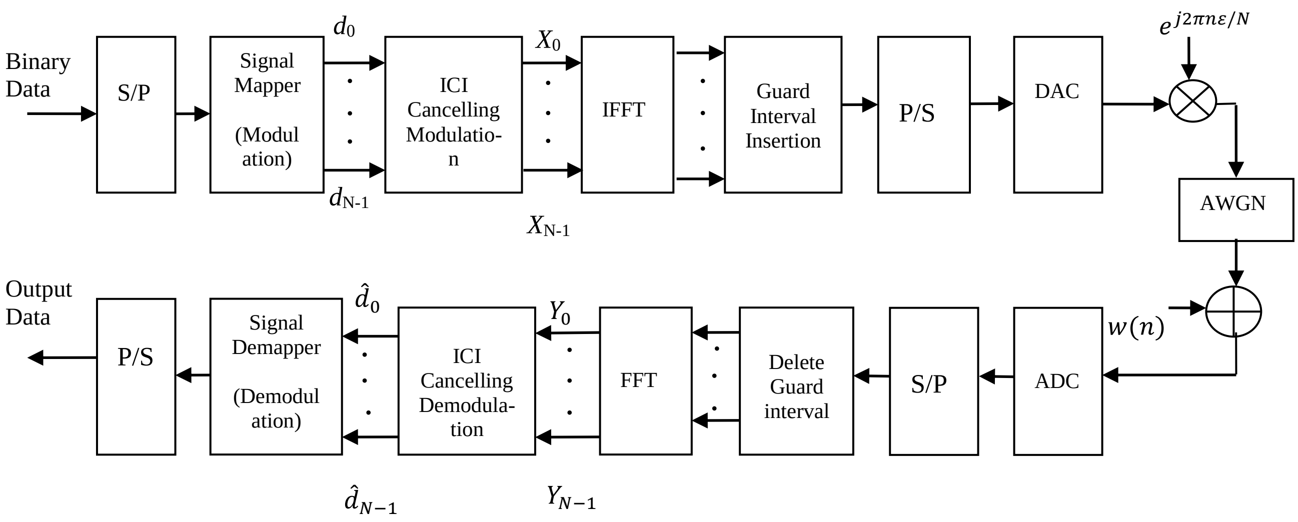

Figure1. Block diagram of the OFDM Transceiver in the presence of frequency offset with ICI self-cancellation

Where, ϵ represents the frequency offset normalized by the subcarrier separation and is given by $\Delta f N T_s$ with Δf being the frequency difference between the transmitted and received carrier frequency, T_s is the symbol period, and $w(n)$ is the AWGN introduced in the channel.

At the receiver, after the FFT block, the received signal on the subcarrier k suffering from the frequency offset can be written as

$$Y(k) = \sum_{n=0}^{N-1} y(n) e^{\frac{-j2\pi nk}{N}}, \qquad k = 0,1,\ldots,N-1 \tag{3}$$

III. ICI IN STANDARD OFDM SYSTEM

In an OFDM system, the received signal on subcarrier k can be further simplified as:

$$Y(k) = X(k)S(0) + \sum_{m=0, m\neq k}^{N-1} X(m)S(m-k) + W_k \tag{4}$$

where W_k is the FFT of $w(n)$. The first and the second term in the right-hand side of (4) represent the desired signal and the ICI components respectively. The sequence $S(m\text{-}k)$ is the complex ICI coefficient between m^{th} and k^{th} subcarriers and can be expressed as [2]:

$$S(m-k) = \frac{\sin(\pi(m+\epsilon-k))}{N\sin(\frac{\pi}{N}(m+\epsilon-k))} \tag{5}$$

$$.\exp(j\pi\left(1-\frac{1}{N}\right)(m+\epsilon-k)$$

The carrier-to-interference ratio (CIR) is the ratio of the signal power to the power in the interference components. It serves as a good indicator of signal quality. It is assumed that the standard transmitted data has zero mean and the symbols transmitted on different sub-carriers are statistically independent. The desired signal is assumed to be transmitted on subcarrier "0". Therefore, the CIR expression for subcarrier $0 \leq k \leq N-1$ can be given as

$$CIR = \frac{|S(k)|^2}{\sum_{m=0, m\neq k}^{N-1} |S(m-k)|^2} = \frac{|S(0)|^2}{\sum_{m=1}^{N-1} |S(m)|^2} \tag{6}$$

IV. ADJACENT SYMBOL REPETITION (ASR)

It has been shown in [2] that the difference between the ICI coefficients of two consecutive subcarriers is very small. This forms the basis of ICI self cancellation scheme. In this scheme one data symbol is modulated onto two consecutive subcarriers. If the data symbol 'a' is modulated on to the 1st subcarrier then '-a' is modulated on to the 2nd subcarrier. Hence, the ICI components generated between the two subcarriers almost gets "self cancelled", hence the name self cancellation method. The transmitted symbols are constrained such that $X(1) = -X(0)$, $X(3) = -X(2)$,…………, $X(N\text{-}1) = -X(N\text{-}2)$,

Using (4), this assignment of transmitted symbols allows the received signal on the subcarrier k to be written as:

$$Y(k) = \sum_{\substack{m=0 \\ m=even}}^{N-2} X(m)[S(m-k) - S(m+1-k)] + W_k \tag{7}$$

and on the subcarrier $(k+1)$

$$Y(k+1) = \sum_{\substack{m=0 \\ m=even}}^{N-2} X(m)[S(m-k-1) - S(m-k)] + W_{k+1} \tag{8}$$

For the majority of $(m\text{-}k)$ values, the difference between $S(m\text{-}k)$ and $S(m+1\text{-}k)$ is very small. Then the ICI signals generated by the subcarrier m will be cancelled out significantly by the ICI generated by subcarrier m+1. This is called ICI cancelling modulation. The ICI can be further reduced by using ICI cancelling demodulation. In this, the signal received at the subcarrier $(k+1)$ (now k an even number) is multiplied by -1 and then summed with the one received at the subcarrier k.

The resultant data sequence is then used for making symbol decision [2] and it can be represented as

$$Y'(k) = Y(k) - Y(k+1)$$
$$= \sum_{\substack{m=0\\ m=\text{even}}}^{N-2} X(m)[-S(m-k-1) + 2S(m-k) - S(m-k+1)] + W_k - W_{k+1} \quad (9)$$

This combination of modulation and demodulation method is called the ICI self cancellation scheme.

This reduction in the ICI signal power level provided by ICI self cancellation scheme leads to a higher CIR compared to standard OFDM system. The CIR for ASR scheme can be easily shown to be

$$\text{CIR} = \frac{|-S(-1) + 2S(0) - S(1)|^2}{\sum_{m=2,4,6}^{N-1} |2S(m) - S(m-1) - S(m+1)|^2} \quad (10)$$

V. SYMMETRIC CONJUGATE SYMBOL REPETITION (SCSR)

In SCSR [10], the modulated symbol X is mapped on subcarriers k and (N - 1 - k). This exploits the odd symmetry nature of the ICI coefficients i.e. $S_k \cong S_{N-1-k}$ for $k \neq 0$. Therefore, the data block becomes X = [X(0), X(1) ,. . . , X(N/2- 1) , -X*(N/ 2 – l),……, -X*(1), -X*(0)] .

The received signal on the subcarrier k can be written as:

$$Y(k) = \sum_{m=0}^{N/2-1} [X(m)S(m-k) - X^*(m)S(N-1-m-k)] + W_k \quad (11)$$

And on the subcarrier (N- k-1)

$$Y(N-1-k) = \sum_{m=0}^{N/2-1} [X(m)S(m-N+1+k) - X^*(m) S(N-1-m-N+1+k)] + W_{N-1-k} \quad (12)$$

The receiver combines the received samples $Y(k)$ and $Y(N - 1 - k)$ and the decision variable becomes

$$Y''(k) = 1/2[Y(k) - Y^*(N-1-k)]$$
$$= 1/2[(S(0) + S^*(0))X(k) + \sum_{\substack{m=0\\ m\neq k}}^{\frac{N}{2}-1} \{S(m-k) + S^*(k-m)\}X(m) - \sum_{m=0}^{\frac{N}{2}-1} \{(S(N-1-m-k) + S^*(m-N+1+k)\, X^*(m)\} + W_k - W^*_{N-1-k}] \quad (13)$$

Its average CIR can be expressed as

$$\text{CIR} = \frac{|S(0) + S^*(0)|^2}{\sum_{m=1,2}^{\frac{N}{2}-1} |(S(m) + S^*(-m)|^2 - \sum_{m=0,1,2}^{\frac{N}{2}-1} \left| \begin{matrix}(S(N-1-m) + \\ S^*(m-N+1)\end{matrix} \right|^2} \quad (14)$$

Since both S_k and S_{N-1-k} may not fade together, this technique offers a diversity gain.

VI. PROPOSED SELF CANCELLATION SCHEME

We know that the difference between the ICI coefficient $S(m-k)$ and its adjacent $S(m+1-k)$ is very small. Therefore, we modulate data (a, -a, -a*, a*) onto four subcarriers (m, m+1, m+2, m+3) where 'a' is a complex data and 'a*' is the complex conjugate of 'a'. That means, the transmitted symbols are constrained so that

$$X(m+1) = -X(m),\ X(m+2) = -X^*(m),\ X(m+3) = X^*(m) \qquad \text{for, } m = 0 \ldots N-1$$

Then the received signal on the subcarrier k becomes

$$Y(k) = \sum_{m=0,4,8}^{N-4} [X(m)\{S(m-k) - S(m+1-k)\} + X^*(m)\{-S(m+2-k) + S(m+3-k)\}] + W_k \quad (15)$$

Similarly, the received signal on the subcarrier k+1 becomes

$$Y(k+1) = \sum_{m=0,4,8}^{N-4} [X(m)\{S(m-k-1) - S(m+1-k-1)\} + X^*(m)\{-S(m+2-k-1) + S(m+3-k-1)\}] + W_{k+1} \quad (16)$$

The received signal on the subcarrier k+2 becomes

$$Y(k+2) = \textstyle\sum_{m=0,4,8}^{N-4} [X(m)\{S(m-k-2) - S(m+1-k-2)\} + X^*(m)\{-S(m+2-k-2) + S(m+3-k-2)\}] + W_{k+2} \quad (17)$$

The received signal the on subcarrier k+3 becomes

$$Y(k+3) = \sum_{m=0,4,8}^{N-4} [X(m)\{S(m-k-3) - S(m+1-k-3)\} + X^*(m)\{-S(m+2-k-3) + S(m+3-k-3)\}] + W_{k+3} \quad (18)$$

This is the modulation of the proposed ICI self cancellation scheme.

To further reduce the ICI, the proposed ICI cancelling demodulation works as follows

1. Each signal at the subcarrier (k+1) is multiplied by '-1' and added to the one at the subcarrier k then the resultant data sequence is given by

$$Y_1(k) = Y(k) - Y(k+1)$$
$$= \textstyle\sum_{m=0,4,8}^{N-4} [X(m)\{2S(m-k) - S(m+1-k) - S(m-k-1)\} + X^*(m)\{-2S(m+2-k) + S(m+3-k) + S(m+1-k)\}] + W_k - W_{k-1} \quad (19)$$

2. We take negative conjugate of the signal transmitted on k+2 subcarrier and conjugate of the signal on k+3 subcarrier and add them to obtain

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$Y_2(k) = Y^*(k+3) - Y^*(k+2)$

$\sum_{m=0,,4,8}^{N-4} [X(m)\{-S^*(m-k-1) + 2\,S^*(m-k) - S^*(m$

$+1-k)\} + X^*(m)\{S^*(m-k-3) - 2S^*(m-k-2)$

$+S^*(m-k-1)\} + W^*{}_{k+3} - W^*{}_{k+2}$ (20)

3. Then the decision variable can be written as

$Y'''(k) = 1/4[Y_1(k) + Y_2(k)]$

$= \{2S(0) - S(1) - S(-1) - S^*(-1) + 2S^*(0) - S^*(1)\}X(k) + \sum_{\substack{m=0,4\\ m\neq k}}^{N-4}[X(m)\{2S(m-k) - S(m+1-k) - S(m-k-1) - S^*(m-k-1) + 2S^*(m-k) - S^*(m+1-k)\} + \sum_{m=0,4,8}^{N-4} X^*(m)\{-2S(m+2-k) + S(m+3-k) + S(m+1-k) + S^*(m-k-3) - 2S^*(m-k-2) + S^*(m-k-1)\}] + W_k - W_{k-1} + W^*{}_{k+2} - W^*{}_{k+3}$ (21)

The theoretical CIR of the proposed ICI self cancellation scheme can be derived as

$$CIR = \frac{|2S(0)\text{-}S(1)\text{-}S(\text{-}1)\text{-}S^*(\text{-}1)+2S^*(0)\text{-}S^*(1)|^2}{\sum_{\substack{m=0,4\\ m\neq k}}^{N-4}|2S(m)\text{-}S(m+1)\text{-}S(m\text{-}1)\text{-}S^*(m\text{-}1)+2S^*(m)\text{-}S^*(m+1)|^2 + \sum_{m=0,4}^{N-4}|\text{-}2S(m+2)+S(m+3)+S(m+1)+S^*(m\text{-}3) - 2S^*(m\text{-}2)+S^*(m\text{-}1)|^2} \quad (22)$$

Since the probability that S_k and S_{N-1-k} will fade together is negligible, the proposed technique also offers a diversity gain. This advantage may not hold in ASR and ACSR schemes, as in these each data symbol is mapped onto a pair of adjacent subcarriers.

VII. SIMULATION RESULTS

We have carried out simulations over MATLAB to verify the effectiveness of the proposed ICI self cancellation scheme. The performance of the proposed ICI self cancellation scheme is evaluated using QPSK and 16-QAM. The total number of subcarriers *N*=1024 are transmitted through AWGN channel, with a symbol duration of 3.2x10^{-6} and the number of symbols used is 100.

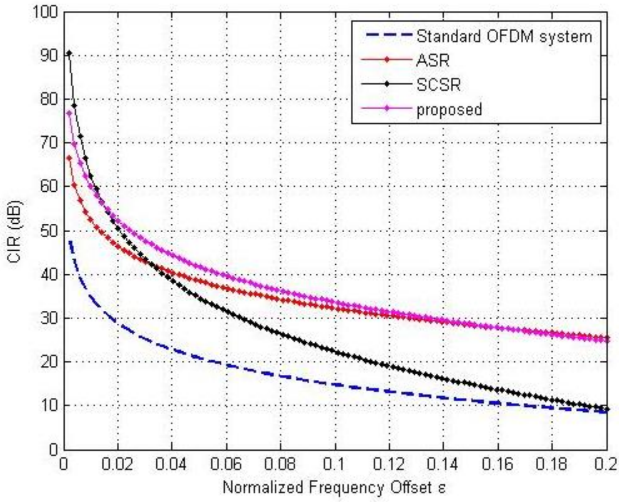

Figure2. CIR comparison of standard OFDM system, adjacent self cancellation technique, SCSR and proposed self cancellation technique.

Fig. 2 shows the comparison of the CIRs for the proposed scheme, standard OFDM system, ASR scheme, and SCSR scheme. The CIR curve of the proposed scheme is evaluated using (22). CIR for standard OFDM system, ASR, and SCSR have been evaluated using (6), (10), and (14) respectively. It is clearly observed that the proposed scheme, in the range $0 < \varepsilon \leq 0.06$, gives about 4-dB CIR improvement over ASR scheme. Also, it gives more than 18-dB CIR improvement in the range $0 < \varepsilon \leq 0.2$ over standard OFDM system. It is also observed that the proposed scheme outperforms SCSR scheme as the frequency offset increases. For example, it gives about 10-dB and 15-dB of CIR improvement at $\varepsilon = 0.12$ and $\varepsilon = 0.2$ over SCSR, respectively.

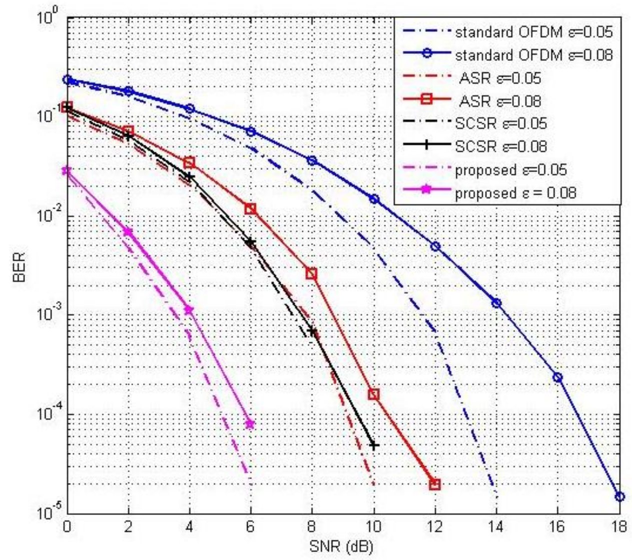

Figure3. Performance comparison between different schemes in AWGN channel for QPSK with ε=0.05 or 0.08.

Fig. 3 shows the BER performance of standard OFDM, ASR, SCSR and proposed self cancellation scheme in AWGN channel for $\epsilon = 0.05$ and 0.08 with QPSK. From the figure it is evident that the proposed scheme shows a remarkable improvement in the BER performance as the frequency offset is increased. It is seen that the proposed scheme offers an SNR gain of 4dB over that of SCSR and around 5dB over ASR at BER of 2×10^{-3} and $\epsilon = 0.08$.

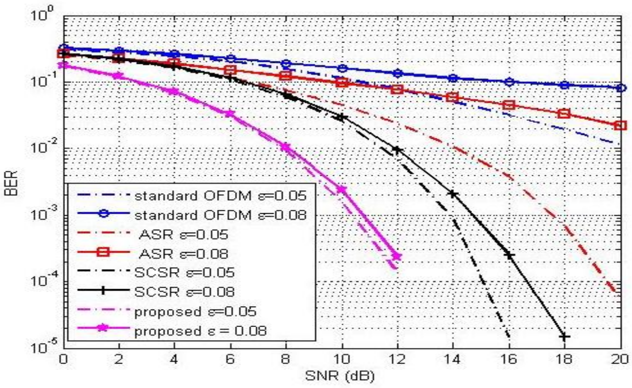

Fig.4 Performance comparison between different schemes in AWGN channel for 16-QAM with ε=0.05 and 0.08.

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The BER performance of standard OFDM, ASR, SCSR and the proposed self cancellation schemes in AWGN channel for ϵ = 0.05 and 0.08 with 16-QAM has been shown in Fig. 4. The figure reveals that with 16-QAM, as compared to QPSK (shown in Fig. 3), for an arbitrary frequency offset the performance of all the systems degrade, but among all the schemes the proposed scheme offers much improved performance. For example, proposed scheme offers an SNR gain of 4dB over that of SCSR and around 12.5dB over ASR at BER of 2×10^{-2} and $\epsilon = 0.08$. This shows that, for higher modulation schemes and higher frequency offsets, the proposed scheme shows significant improvement in BER performance over standard OFDM and all the existing ICI self cancellation schemes.

VIII. CONCLUSION

This paper proposes a new ICI self cancellation scheme for combating the impact of frequency offset on OFDM systems. The simulation results suggest that the proposed scheme gives better BER performance than the ASR and SCSR self cancellation schemes in AWGN channel. Furthermore, the proposed scheme provides significant CIR improvement. Therefore, it can be concluded that with the proposed scheme the need for channel equalization for reducing ICI can be eliminated and hence is easy to implement without increasing the system complexity. In the proposed scheme, the data needs to be transmitted over four different subcarriers resulting in the reduced bandwidth efficiency. However, in the presence of larger frequency offsets, where the communication can be greatly affected, the OFDM system using the proposed ICI self-cancellation scheme performs much better than the standard OFDM system and the OFDM systems using existing ICI self cancellation schemes.

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